Indian J. Phys. **78(8)**, 827-831 (2004)

AN INTERNATIONAL JOURNAL IJP

A proposal for the development of a fiber-optic interferometer for the determination of piezoelectric coefficient

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Abstract : The paper deals with the fabrication and characterization of different piezoelectric ceramics, polymers or their composites by finding their nonzero electromechanical coupling coefficients, the piezoelectric coefficients d_{ij} with the help of a self designed, sensitive, all-fiber Mach-Zehnder interferometer based on the principle of Pockels effect or acousto-optic effect with the aim of finding suitable materials in devices like varisters, electro-optic and acousto-optic modulators, transparent conductors, ultrasonic transducers, masers, phospher and gas igniters *etc.*

Keywords : Pockels effect, acousto-optic effect, Mach-Zehnder interferometer, electromechanical coupling coefficients, perovskites, XRD, SEM image.

PACS Nos. : 07.60.Ly, 42.81.Wg.77.65.Bn

1. Introduction

Optical fibers are finding wide-range applications in thousands of kilometers terrestrial connection lines hierarchy where secure, interference-free transmission is required [1]. Confined and almost lossless propagation in silica-glass fibers as the transmission medium for long distance high-data-rate optical communication has almost revolutionized the art and practice of communication [2,3]. During recent years, a global hunt is on for better piezoelectrics as well as their copious supply because piezoelectric devices such as transducers, ultrasonic generators, microphones, phonograph pick-ups, resonators for frequency control or filters, dynamical and volatile memory components, gas igniters, piezoelectric transducers, impact printer head sensors *etc.* have become of outstanding technical importance. The present work aims at fabricating and characterizing different piezoelectric ceramics, polymers or their composites with the help of a self-designed sensitive all-fiber Mach-Zehnder interferometer based on electro-optic and acousto-optic effects. The materials chosen are ferroelectrics of the perovskite family of the general formula ABO_3 (A = monovalent, B = triad or pentavalent ions), PZT ceramics with compositions of the type $Pb(Zr_xTi_{1-x})O_3$ $(0 < x < 1)$, PLZT, PZT/PVDF composites, nylons, PTFE, PMMA with and without the binders such as PVA, naphthalene, resin and paraffin wax.

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2. Experimental details

The interferometer is being designed from the type HP11980A with opt 012 connector interface in which, taking into consideration the large wavelength [4], a semiconductor laser of the type HP8154SM and opt 002 is used as the source of optical power for the single mode optical fiber of the type HP11886A. The fiber is split into two arms, called reference and sensor arms, with the help of the 3db directional coupler of the type HP11890A with almost equal power flowing through both the arms. Both the arms contain calibrated variable optical attenuators of the type HP8157A. In the reference arm, a phase shifter calibrated in terms of known-measurands such as voltage (in case of electro-optic modulation effect to be produced) or total acoustic power (in case of acousto-optic modulation to be produced) is attached as per the requirement. The fiber of the sensor arm is wrapped on any one of the synthesized piezoelectric materials whose non-zero coefficients are to be determined. For the determination of piezoelectric coefficients of polymers, a thin film is to be deposited on a hollow polyethene/polystyrene cylinder on which the fiber could be wrapped. The outputs of both the arms fed to the inputs of PIN photo detectors of the type 11982A which cover a wavelength range of 1200 nm to 1600 nm and a bandwidth from dc to 15 GHz with a sensitivity of 300 volts/watt kept in each arm whose outputs are fed into the two inputs of a difference amplifier. The output of the difference amplifier is fed to the CRO or network analyzer. In the experiment, the null in the detector output is obtained first by sensor arm isolated from the 'external influence' and then the external influence such as voltage/acoustic power is 'put on' so that the fiber expands radially – thus inducing a phase change. Now, either the voltage or the acoustic power, as the case may be, is changed to get null in the detector output again. The difference of the two readings on the scale attached with modulators gives the phase shift created only by the sample itself and hence the electromechanical coupling coefficients of the sample kept in the sensor arm. The sensitivity of the interferometer to pressure is enhanced by the use of rubber or plastics on the hollow polythene/polystyrene cylinder [5]. The inclusion of modulators in both the arms of the interferometer owes its origin to a similar Microwave Interferometer designed and developed by Prasad and Sharma [6]. In the recent past several such interferometers, in different modified forms suited to different purposes, have been designed and developed [7–13]. The theory of both the modulators may be given, in brief, as follows :

(a) Electro-optic effect and electro-optic modulators :

It is a well-established fact that due to the application of an electric field across an optical medium, the redistribution of electrons within it gets distorted so that the polarizability and hence the refractive index of the medium changes anisotropically and consequently the new optic axes of changed lengths and orientations of each of its principal axes may be produced in naturally doubly refracting crystals or to make naturally isotropic crystals, for example GaAs, doubly refracting in the form :

$$\square\,(1/n^2) = [dE] + [pE^2], \qquad (1)$$

where d is linear electro/optic coefficient and p is the quadratic electro-optic coefficient. First term on r.h.s. of the above equation represents 'Pockels effect' and the second term represent 'Kerr effect'. Any transparent crystal lacking a center of symmetry exhibits the Pockels effect [14]. The coefficients in the d_{ij} matrix are given as :

$$P_i = \sum d_{ij} T_j \qquad (2a)$$

or

$$s_i = \sum d_{ij} E_i (i = 1, 2, 3; j = 1, 2, 3...6) \qquad (2b)$$

which indicates that the application of a mechanical stress tensor T produces not only a mechanical strain s but also an electric polarization vector P (direct effect) and similarly the application of an electric stress E causes not only P but also a mechanical strain (s) (converse effect).

The non-vanishing coefficients in d_{ij} matrix are d_{13} and d_{33} for ferroelectrics having perovskite structure such as $BaTiO_3$, $LiNbO_3$, $LiTaO_3$, $NaTaO_3$, $KTaO_3$, $NaCoO_3$, $KCoO_3$, and their mixed oxides such as KTN (*e.g.* $KTa_{0.65}Nb_{0.35}O_3$). On applying an electric field E_z along the optic axis, chosen as the z-axis (say), the refractive indices for light wave polarized along the crystallographic x, y and z directions are given as :

$$n_x = n_o - \tfrac{1}{2}\, n_0^3 d_{13} E_z, \qquad (3a)$$

$$n_y = n_o - \tfrac{1}{2}\, n_0^3 d_{13} E_z \qquad (3b)$$

and

$$n_z = n_e - \tfrac{1}{2}\, n_e^3 d_{33} E_z, \qquad (3c)$$

where n_o and n_e are the refractive indices for the ordinary and extraordinary waves.

Thus for the incident light wave polarized along the z-direction, the application of an electric field along z-direction will lead to phase modulation of the beam and the output light will still be polarized along the z-direction. When the surface of the crystal (say $LiNbO_3$) is normal to the x-directed principal axis, waveguides are along the y-direction and the electric field in the waveguides is z-directed (TE wave), then the d_{ij} coefficient used for the modulation is d_{33}. The applied field does not change the orientation of the principal axis of the permittivity tensor ellipsoid [15]. Thus the phase difference $\square\phi$ between the arms of the interferometer due to the sample kept in the reference arm of the interferometer is given by :

$$\square\phi = \omega/2c.d_{33}.n_e^3 L.E_Z = \pi n_e^3.V\pi.l/\lambda_0.W \qquad (4)$$

where λ_0 = wavelength of the wave in free space, W = width of the guide, V_π = voltage applied to produce a phase shift of π (path difference of $\lambda/2$) in the output beam.

For a null deflection in the output of the developed interferometer of our scheme, $\square\phi = \pi$. Thus, the above eq. (4) gives

$$d_{33} = \lambda_0.W/2n_e^3.L.V\pi. \quad (5)$$

Although a phase difference of π produces antisymmetric higher order modes in the output waveguide, in a single mode waveguide, which do not allow to propagate higher order modes, the effect on this account may be ignored in our case. Thus knowing all the remaining quantities in eq. (5), or alike, the coefficients of the d_{ij} matrix according to the alignment of the experimental set could be determined.

(b) Acousto-optic effect and acousto-optic modulators :

Acousto-optic effect is the change in the refractive index of a medium caused by the mechanical strains accompanying the passage of an acoustic (strain) wave *e.g.* ultrasonic wave through the medium. The strain and hence the refractive index varies periodically with the wavelength $\wedge$ equal to that of the acoustic wave due to the photo-elastic effect, which is proportional to the square of the total acoustic power. In this case the acoustic wave sets up a diffraction grating within the medium and the ruling depth is related to the amplitude of the acoustic modulating wave *i.e.* the stress produced. Restricting ourselves to lower order *i.e.* the 1st order of the diffraction band, the Bragg angle θ_B is given by :

$\theta_B = \sin^{-1}(m\lambda/2\wedge) = \sin^{-1}(\lambda/2\wedge)$ (m = order of the diffraction band = 1)

$$\Rightarrow \cos\theta_B = (1 - \lambda^2/4\wedge^2)^{1/2} = (4\wedge^2 - \lambda^2)^{1/2}/2\wedge$$

the phase shift ϕ is given by

$\phi = 2\sin^{-1}(\eta^{1/2})$($\eta$ = % diffraction efficiency of the grating).

The change in refractive index is given by

$$\Delta n = \phi\lambda \cos \theta_B/2\pi L = \phi\lambda(4\wedge^2 - \lambda^2)^{1/2}/4\wedge L.$$

Now, for a complete coupling between the incident and diffracted beam, $\phi = \pi$.

Thus, $\Delta n = \lambda(4\wedge^2 - \lambda^2)^{1/2}/4\wedge L. \quad (6)$

Also, from the preliminary theory of Pockels effect, one has

$$\Delta n = -n^3ps/2, \quad (7)$$

where s is the strain components given by $s = (2P_a/\rho v_a^3 A)^{1/2}$,

finally giving

$$p = -\lambda\{(4\wedge^2 - \lambda^2)\rho v_a^3 A/2pa\}^{1/2}/2\wedge Ln^3, \quad (8)$$

where

L = length of the sample in the modulator,

p = strain optic component of the tensor similar to d_{ij},

P_a = acoustic power,

A = area of the transducer,

ρ = density of the medium,

v_a = velocity of the acoustic wave.

Thus, knowing all other quantities in eqs. (8), strain-optic component of the tensor p of the test material could be determined. Suitable materials chosen for this effect to be easily observed and handled are $LiNbO_3$, $PbMo_{04}$, Te_0 and their composites.

However, the acousto-optic modulators are not so fast as the electro-optic modulators, but the voltage required for operation is small compared to that for their electro-optic counterparts and hence acousto-optic modulators are easier to handle with.

(c) Theory for the enhancement of the sensitivity of the interferometer :

The propagation of optical waves in a single mode fiber resembles a ray traveling down the center of the fiber with a velocity C/n (n being the average refractive index of the core and claddings of the fiber) so that the phase in radians associated with a length L of the fiber is given by

$$\phi = 2\pi nL/\lambda_0. \quad (9)$$

Consequently the phase change $\Delta\square$ is given by

$$\Delta\square = \square\Delta L + L\Delta\square \approx \square\Delta L \quad (10)$$

(neglecting the second term in comparison with the 1st, $\square$ being the propagation constant).

In the context of our developed interferometer, let us consider the form of the output expected. The total signal amplitude in the detector output (R_s) is given by the product of the term and its own complex conjugate.

$$\Rightarrow R_1 \propto [A_s^2 + A_r^2 + 2A_sA_r \operatorname{Cos}\Delta\square],$$

where the subscripts s and r refer to signal and reference respectively.

Thus, the response of the 1st detector is given by

$R_1 \propto [A_s \exp\{i(wt + \Delta\Box)\} + A_r \exp(iwt)] \times [A_s \exp\{-i(wt + \Delta\Box)\} + A_r \exp(-iwt)]$.

For simplicity, let us take $A_s = A_r = A$ (say),

$$R_1 \propto 2A^2(1 + \mathrm{Cos}\Delta\Box). \quad (11)$$

Similarly, the response of the second detector is given by

$$R_2 \propto 2A^2 \{1 + \mathrm{Cos}(\Delta\Box + \pi)\}$$

$$\Rightarrow R_2 \propto 2A^2 (1 - \cos\Delta\Box). \quad (12)$$

The above two eq. (11) and (12) yield

$$(R_1 - R_2) \propto 4A^2.\cos\Delta\Box. \quad (13)$$

Thus in effect, by taking the difference between two outputs signals, one doubles the sensitivity of the interferometer. Use of the above theory has been made in the developed interferometer of our scheme. The schematic diagram of our interferometer (Figure 1) is given below :

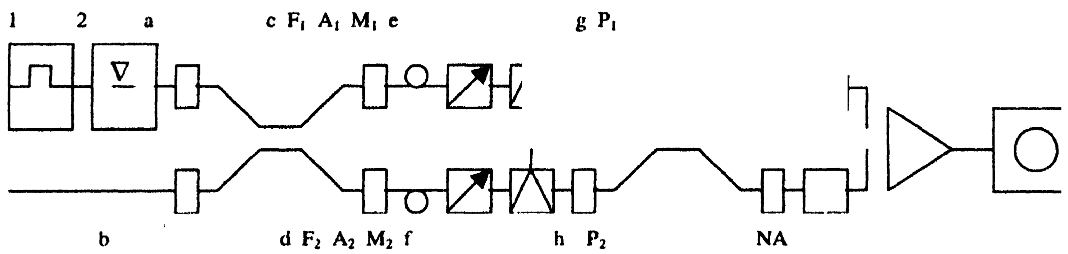

Figure 1. Schematic Diagram of the Interferometer. 1–Pulse generator; 2–Injection laser diode; a, b, c, d, e, f, g, and h–fiber connectors; dc_1, dc_2, –3db directional couplers; F_1, F_2-single mode optical fibers; A_1, A_2, –continuous optic attenuators; M_1, M_2–electro-optic/acousto-optic modulators, P_1, P_2–PIN photodetectors; DA–difference amplifier; NA–CRO/network analyzer.

(d) Synthesis of materials :

Some of the ceramics for our use have already been prepared in our laboratory and some others are underway of preparation *via* high temperature solid state reaction technique from their constituent oxides, carbonates and nitrates in stoichiometric proportions. Thin films are to be prepared with the help of Lymbold Heracus Univex 300 type along with digital monitor of thickness of deposition, where the rate is 30 nm/minute and spin cast rate of 200 r.p.m. under the vacuum of 10^{-5} Torr. The experimentation is underway. The piezoelectric phase characterization of some of the samples through XRD has already been done and for some others the work is in progress. Same is the situation with the surface morphology by SEM images. The design and development of the interferometer is almost complete and now the sensitivity is being tested through standard materials and further works on new materials are expected to be reported soon.

(e) Contextual significance of the work and rationale for its choice :

As reported to earlier, ferroelectrics of the perovskite family find their wide-range applications in memory devices, impact printer head sensors *etc.*

PZT and PLZT offer their applications in devices with improved opto-electronic and piezoelectric properties such as in electric wave filters [16].

Piezoelectric oxides of Tungsten-Bronze (TB) family having negative temperature coefficient of resistance give the candidature for use as thermistors and pyrometers [17,18].

Strontium Barium Niobate (SBN) type modified as SBN50 have also shown their potentialities of being used in electro-optic devices [19] .

PLZT nano-ceramics offer negative temperature coefficient of resistance – thus giving a scope for their use in dynamic memory elements [20].

Layered transition metal oxides like $LiCoO_2$, $LiMnO_4$ *etc.* have shown their potentialities for their use as cathode and ionically conducting solids (polycrystalline ceramics, polymers and their composites) as the solid electrolyte for solid (polycrystalline ceramics, polymers and their composites) as the solid electrolyte for solid state batteries [21].

Thin films of n-type as well as p-type transparent conducting oxides (TCO) could find their applications in 'functional windows' [22,23].

3. Conclusions

The present study gives a theoretical perspective for a sensitive method for the determination of electro-mechanical coupling coefficients of synthesized useful piezoelectric materials. The theoretical work will be corroborated subsequently by experimental one.

References

[1] J M Senior *Optical Fiber Communication Principles and Practice* (2nd edn.) (India : Prentice Hall) (2001)

[2] S E Miller and I P Kaminow (eds) *Overview and Summary of Programs Optical Fiber Telecommunications* (New York : Academic) Press **Vol. II** p1 (1988)

[3] J M Senior and T S Ray *J. Technol. Management* 5 71 (1990)

[4] T P Lee *Proc. IEEE* **79** 253 (1991)

[5] G Busch and P Scherrer *Naturwiess* **23** 737 (1935)

[6] A Prasad and K P Sharma *Indian J. Pure Appl. Phys.* **28** 403 (1990)

[7] K P Koo and G M Sigel *J.Quant. Elect.* **QE-18** 670 (1982)

[8] Leilababy P Akhavan, J D C Jones and D A Jackson *Interferometric Strain Measurement using Optical SPIE Proc.* **586** 230 (1985)

[9] M Imai, J Shimizu, Y Ohesuka and A Odajima *J. Light Tech.* **Vol. LT-5** p926 (1987)

[10] D A Jackson and J D C Jones *Interferometers* in *B Culshaw and J P Dakin* (eds.) *Optical Fiber Sensors : Systems and Applications* (New York : Artech House) p329 (1989)

[11] W J Wanj, S Honkanen, S I Najafi and A Tervonen *Appl. Phys. Lett.* **6** 150 (1992)

[12] S I Najafi, P Lefevre, J Albert, S Honkanen, A Vahid Shahidi and W J Wang *Appl. Opt.* **31** 3381 (1992)

[13] G Zhang, S Honkanen, A Tervonen, S I Najafi and P Katila *Pure Appl. Optics* (1996) (accepted for publication)

[14] F Pockels *Abh Goethingen Ges. D. wiss* **39** 169 (1894)

[15] Mc Mohan and Cielo *Appl. Opt.***18** 3720 (1979)

[16] S B Deshpande and P Roychoudhary *Proc. 2nd Natl. Conf. Ferroelectrics* p2 (1982)

[17] A K Ghosh and T K Munshi *Indian J. Phys.* **77A** 633, 637 (2003)

[18] N K Singh and R N P Choudhary *Indian J. Phys.* **77A** 627 (2003)

[19] P K Patro, B D Deshmukh, A R Kulkarni and C S Harendranath *Proc. C.M.Days* p66 (2002)

[20] P K Datta *Proc. National Conference on Physics of Condensed Matters* (NCPCM) **IT-5** p4 (2003)

[21] A K Thakur *Proc. NCPCM* **IT-6** p5 (2003)

[22] H Kawazoe, M Yasukawa, H Hyoto, H Yanagi and H Hosono *Nature* **389** 939 (1997)

[23] A N Banerjee and K K Chattopadhayaya *Proc.*